J Arid Land (2023) 15(3): 327–343
https://doi.org/10.1007/s40333-023-0096-2

Science Press Springer-Verlag

Modern pollen assemblages and their relationships with vegetation and climate on the northern slopes of the Tianshan Mountains, Xinjiang, China

ZHANG Wensheng[1], AN Chengbang[1*], LI Yuecong[2], ZHANG Yong[1], LU Chao[1], LIU Luyu[1], ZHANG Yanzhen[1], ZHENG Liyuan[1], LI Bing[2], FU Yang[1], DING Guoqiang[1]

[1] Key Laboratory of Western China's Environmental Systems, Ministry of Education, College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China;
[2] College of Geographical Sciences, Hebei Normal University, Shijiazhuang 050024, China

Abstract: The reconstruction of paleovegetation and paleoclimate requires an understanding of the relationships between surface pollen assemblages and modern vegetation and climate. Here, we analyzed the characteristics of surface pollen assemblages across different vegetation zones in the Tianshan Mountains. Using surface pollen analysis and vegetation sample surveys at 75 sites on the northern slopes of the Tianshan Mountains, we determined the correlation between the percentage of dominant pollen types and the corresponding vegetation cover. Redundancy analysis was used to investigate the relationships between surface pollen assemblages and environmental factors. Our results show that the Tianshan Mountains contain several distinct ecological regions, which can be divided into five main vegetation zones from low to high altitudes: mountain desert zone (Hutubi County (HTB): 500–1300 m; Qitai County (QT): 1000–1600 m), mountain steppe zone (HTB: 1400–1600 m; QT: 1650–1800 m), mountain forest zone (HTB: 1650–2525 m; QT: 1850–2450 m), subalpine meadow zone (HTB: 2550–2600 m; QT: 2500–2600 m), and alpine mat vegetation zone (HTB: 2625–2700 m; QT: 2625–2750 m). The surface pollen assemblages of different vegetation zones can accurately reflect the characteristics of the mountainous vegetation patterns on the northern slopes of the Tianshan Mountains when excluding the widespread occurrence of Chenopodiaceae, *Artemisia*, and *Picea* pollen. Both average annual precipitation (P_{ann}) and annual average temperature (T_{ann}) affect the distribution of surface pollen assemblages. Moreover, P_{ann} is the primary environmental factor affecting surface pollen assemblages in this region. A significant correlation exists between the pollen percentage and vegetation cover of *Picea*, Chenopodiaceae, *Artemisia*, and Asteraceae. Moreover, *Picea*, Chenopodiaceae, and *Artemisia* pollen are over-represented compared with their corresponding vegetation cover. The Asteraceae pollen percentage roughly reflects the distribution of a species within the local vegetation. These results have important implications for enhancing our understanding of the relationship between surface pollen assemblages and modern vegetation and climate.

Keywords: surface pollen assemblages; environmental factors; vegetation cover; redundancy analysis; Tianshan Mountains

Citation: ZHANG Wensheng, AN Chengbang, LI Yuecong, ZHANG Yong, LU Chao, LIU Luyu, ZHANG Yanzhen, ZHENG Liyuan, LI Bing, FU Yang, DING Guoqiang. 2023. Modern pollen assemblages and their relationships with vegetation and climate on the northern slopes of the Tianshan Mountains, Xinjiang, China. Journal of Arid Land, 15(3): 327–343. https://doi.org/10.1007/s40333-023-0096-2

*Corresponding author: AN Chengbang (E-mail: cban@lzu.edu.cn)
Received 2022-08-20; revised 2023-01-19; accepted 2023-02-10

1 Introduction

As one of the major proxies for the study of climatic environmental change, pollen plays an irreplaceable role in vegetation and climate reconstruction for the Quaternary Period (2.58 Ma–present) (Zhang et al., 2019, 2022; Li et al., 2020; Chen et al., 2021a; Zhao et al., 2021). Because different plant species produce pollen that varies substantially in production, dispersal ability, deposition rate, and preservation conditions, indicators such as the percentage and concentration of surface pollen are not necessarily equivalent to the distribution and amount of vegetation at a certain time (Ge et al., 2017; Li et al., 2017; Chen et al., 2021b; Zhang et al., 2021). Counting surface pollen assemblages to interpret, recover, and quantitatively reconstruct paleovegetation and paleoclimate culminates in inaccurate results (Xu et al., 2006, 2015; Li et al., 2017; Zhang et al., 2018). Therefore, it is crucial to accurately reveal the relationship between surface pollen assemblages and modern vegetation and climate, which is conducive to objectively interpreting the indicative significance of pollen and provides basic information for converting stratigraphic pollen data into vegetation abundance and climate indicators for a given period. Moreover, this result has an important role in improving the accuracy of paleoclimate studies, and provides a reference for reconstructing the environmental evolution since the Holocene. Therefore, exploring the relationship between surface pollen assemblages and the present-day vegetation and climate in a region has important theoretical and applied values for Quaternary pollen studies (Chevalier et al., 2020; Ge et al., 2020; Li et al., 2020; Zhang et al., 2021).

Mountains cover approximately 30% of the global land area and play an important role not only in hydrological protection, climate regulation, and biodiversity conservation but also in product supply and socioeconomic development (Deng et al., 2015; Feng et al., 2021). Moreover, mountains are important for studying the relationship between surface pollen assemblages and modern vegetation and climate because of their topography and air transport mechanisms for pollen dispersal (Lu et al., 2011; Pan et al., 2013; Yang et al., 2016). Mountain vegetation and soil are characterized by notable vertical distributions and large regional differences; thus, they have a considerable impact on pollen dispersal, transport, and deposition. Therefore, mountains are an important area for studying the processes and patterns of paleoenvironmental evolution in China (Yang et al., 2011). The mountainous vertical zone is 1000 times narrower than the horizontal zone, with a large gradient of variability and responsiveness to climatic variables, which is ideal to explore the characteristics of surface pollen distribution influenced by climatic factors (Yu and Liu, 1997). Modern pollen assemblages in mountainous areas can be distinguished by dominant vegetation zones at different altitudes, which is a major criterion for reconstructing paleovegetation and paleoclimate using fossil pollen (Davies and Fall, 2001; Yu et al., 2001; Yang et al., 2016). Niu et al. (2022) concluded that the surface pollen assemblage in the western Tianshan Mountains is consistent with the distribution of modern vegetation, and that altitude, average annual precipitation (P_{ann}), and annual average temperature (T_{ann}) comprehensively influence the distribution of the surface pollen assemblage in this region. The Tianshan Mountains, located in the arid area of Central Asia, are an important geographic and vegetative horizontal zoning boundary in the Xinjiang Uygur Autonomous Region, China, possess diverse vertical vegetation zones, and provide a type area for exploring the relationship between surface pollen assemblages of different vegetation zones and corresponding vegetation cover (Zhao and Li, 2013; Yang et al., 2016; Yao et al., 2019).

In recent years, several studies have explored the relationships among surface pollen assemblages, vegetation, and climate in areas around the Tianshan Mountains; results have been obtained from surface pollen studies in the Xarxili Nature Reserve (Yang et al., 2019), Small Yourdusi Basin (Chen et al., 2012), Shihezi Nanshan area (Zhang et al., 2013), Urumqi River headwaters area (Yang et al., 2004), Turpan area (Wang et al., 2017), Eren Habirga Mountains (Zhao et al., 2019), Bogda Mountains (Yao et al., 2021a), Tianchi Lake area (Yang et al., 2016), central Tianshan Mountains (Lang et al., 2020), and western Tianshan Mountains (Yao et al., 2019). In summary, existing studies have conducted qualitative and quantitative analyses of the spatial distribution patterns of surface pollen, characteristics of pollen assemblages in different

vegetation belts, and surface pollen–vegetation–climate relationships in the Tianshan Mountains (Yao et al., 2019; Niu et al., 2022). Surface pollen studies in the Tianshan Mountains have mainly been conducted on a large scale, with pollen shown to vary substantially among vegetation belts owing to latitude, altitude, and topography; these pollen assemblages match the modern vegetation distribution, but the pollen percentages of individual genera are not linearly related to vegetation cover (Luo et al., 2009; Wei and Zhao, 2016; Yang et al., 2016). Such studies have accumulated rich datasets for the study of surface pollen in the Tianshan Mountains and laid a solid foundation for the quantification of Quaternary pollen in this region.

However, existing surface pollen studies remain sparse given the extensive area of the Tianshan Mountains. In addition, the spatial distribution of existing surface pollen sites is uneven and the site arrangement is discontinuous; in particular, surface pollen studies on the northern slopes of the Tianshan Mountains are relatively weak (Lang et al., 2020; Yao et al., 2021a). Most of the existing studies on stratigraphic fossil pollen with continuous and stable deposition have focused on the northern slopes of the Tianshan Mountains (Yao et al., 2015), and most of these previous studies performed only qualitative analysis of pollen, with few quantitative studies. One important reason for this inadequacy is the relatively low availability of modern surface pollen on the northern slopes of the Tianshan Mountains (Zhang et al., 2022). Therefore, the study of modern surface pollen on the northern slopes of Tianshan Mountains provides basic information for the retrieval of regional paleovegetation and paleoenvironment data, as well as parameters for quantitative paleoclimate reconstruction using pollen. The impact of anthropogenic activities is also increasing with the development of agriculture and animal husbandry (Huang et al., 2018; Li et al., 2021), which exerts a certain influence on the transport, deposition, and preservation of surface pollen. Thus, several issues remain that warrant further research and exploration to advance our understanding of the relationships between surface pollen assemblages and modern vegetation and climate.

Here, we used 75 surface pollen samples from the main vegetation types in Qitai County (QT) of the eastern Tianshan Mountains, and Hutubi County (HTB) of the central Tianshan Mountains, combined with plant community sample surveys. We analyzed the characteristics of surface pollen assemblages in different vegetation zones, correlation between the percentage of dominant pollen types and the corresponding vegetation cover, and representativeness (R-value) of dominant pollen types. Redundancy analysis (RDA) revealed the environmental factors affecting the distribution of surface pollen assemblages. This study therefore provides a scientific basis for using pollen data to research regional paleovegetation and paleoenvironment on the eastern and central northern slopes of the Tianshan Mountains.

2 Study area

The Tianshan Mountains comprise one of the largest mountain systems in Central Asia, spanning 2500 km from east to west, with a width of 250–350 km from north to south. The Tianshan Mountains consist of three mountain chains: southern Tianshan Mountains, central Tianshan Mountains, and northern Tianshan Mountains, as well as several intermontane basins that situate among these ranges (Hu, 2004). The Tianshan Mountains show considerable fluctuations in altitude and temperature; the T_{ann} on the northern slopes is 2.5°C–5.0°C. Precipitation is also unevenly distributed, with the P_{ann} of approximately 200 mm on the northern slopes; more precipitation occurs in the mountains than on the plains, and the P_{ann} in the foothills is more than 200 mm (Ran et al., 2015; Yao et al., 2021b). The seasonal variation in precipitation is extreme, with most rainfall in the summer (Long et al., 2017). The Tianshan Mountains intercept the warm and humid airflow from the Atlantic Ocean and Arctic Ocean, which, combined with the gradient change in temperature with increasing altitude, creates a clear vertical zoning phenomenon. According to previous researches (Lang et al., 2020; Yao et al., 2021a, b) and fieldwork data, we divided the vegetation types in this study area into five vegetation zones based on altitude. These vegetation zones, from highest to lowest altitude, are as follows: alpine mat vegetation zone (>2600 m), subalpine meadow zone (2500–2600 m), mountain forest zone (1700–2500 m),

mountain steppe zone (1400–1700 m), and mountain desert zone (500–1400 m) (Comprehensive Investigation Team of Xinjiang and Institute of Botany, Chinese Academy of Sciences, 1978). The mountain desert zone is dominated by *Artemisia* and Chenopodiaceae, primarily *Ceratocarpus arenarius* L., *Chenopodium glaucum* L., *Seriphidium borotalense* (Poljak.) Ling et Y. R. Ling, and *Seriphidium kaschgaricum* (Krasch.) Poljak.. The mountain steppe zone is dominated by Poaceae, such as *Stipa capillata* L., *Festuca valesiaca* subsp. *sulcata* (Hackel) Schinz & R. Keller., and various *Artemisia* and Chenopodiaceae plants. *Picea schrenkiana* Fisch. et Mey. dominates the mountain forest zone, with *Betula tianschanica* Rupr. and *Populus tremula* L. occurring occasionally, and the grass under the forest mainly includes *Calamagrostis epigeios* (L.) Roth, *Bromus inermis* Leyss., and *Uraria crinita* (L.) Desv. ex DC.. The subalpine meadow zone is mainly occupied by *Kobresia capillifolia* (Decne.) C. B. Clarke, *Kobresia myosuroides* (Villars) Foiri, *Dactylis glomerata* L., *Polygonum viviparum* L., and *Koenigia alpina* (All.) T. M. Schust. & Reveal, among other species. The alpine mat vegetation zone mainly comprises *Sibbaldia tetrandra* Bge., *Thylacospermum caespitosum* (Camb.) Schischk., *Saussurea japonica* (Thunb.) DC., and *Potentilla biflora* Willd. ex Schlecht. among other species.

3 Materials and methods

3.1 Vegetation survey and surface sample collection

Following previous studies and field surveys, we collected surface samples according to topographic and geomorphological differences and the typicality of plant communities in the study area. Samples were collected in 2021 within modern vegetation communities throughout the eastern and central northern slopes of the Tianshan Mountains (Fig. 1). The sampling sites were located in areas with the least amount of anthropogenic disturbance. We collected surface samples according to the "plum point method", taking surface samples of 1–2 cm at the four corners and center of each sample square. One sample square was created for every 25–100 m of altitude gain. The vegetation zone at low altitude is wider, thus one sample was taken every 50–100 m; the vegetation zone at high altitude is narrower, thus one sample was taken every 25 m. A total of 75 samples were collected (Fig. 1; Table 1): 30 samples in QT and 45 samples in HTB. The altitudes of these sampling sites ranged from 500 to 2750 m. The latitude, longitude, and altitude of each sampling site were recorded using the Global Positioning System, and a vegetation quadrat survey was carried out at each sampling site. According to the actual situation of the vegetation zone, we set different sampling areas, i.e., 10 m×10 m for the mountain steppe, mountain desert, and mountain forest zones, 5 m×5 m for the subalpine meadow zone, and 20 m×20 m for the alpine mat vegetation zone. The main plant species and plant cover in each sampling area were recorded.

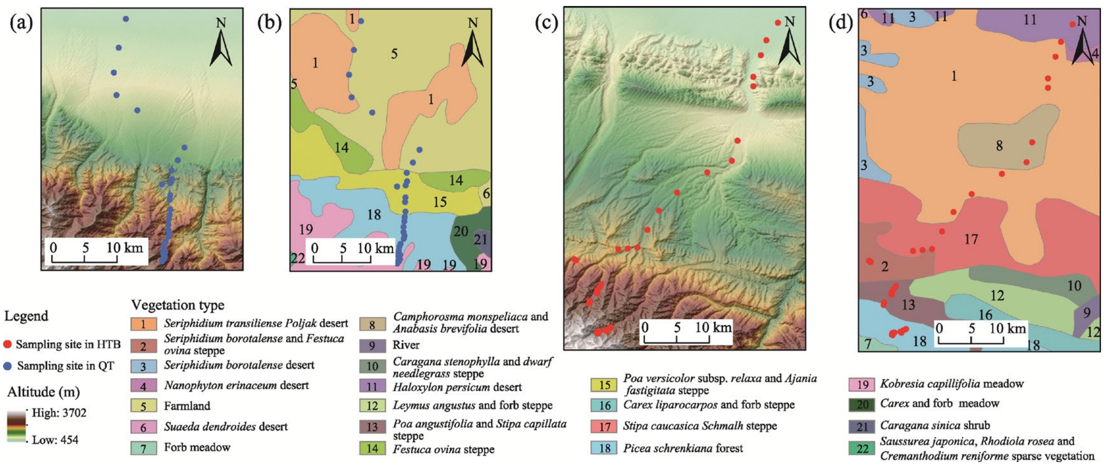

Fig. 1 Location (a and c) and vegetation distribution (b and d) of surface pollen sampling sites in the regions of Qitai County (QT) and Hutubi County (HTB) (drawn from Hou (2001))

Table 1 Longitude, latitude, and altitude of the sampling sites

Lab number	Sample number	Latitude	Longitude	Altitude (m)	Lab number	Sample number	Latitude	Longitude	Altitude (m)
1	HTB1	44°09′19″N	86°34′16″E	500	39	HTB39	43°43′31″N	86°19′19″E	2675
2	HTB2	44°07′51″N	86°33′18″E	600	40	HTB40	43°43′31″N	86°19′20″E	2700
3	HTB3	44°06′37″N	86°32′51″E	650	41	QT1	43°52′26″N	89°32′40″E	1000
4	HTB4	44°04′49″N	86°32′14″E	700	42	QT2	43°49′45″N	89°32′01″E	1100
5	HTB5	44°04′02″N	86°32′13″E	750	43	QT3	43°47′25″N	89°31′33″E	1200
6	HTB6	43°59′31″N	86°30′55″E	850	44	QT4	43°45′18″N	89°31′47″E	1300
7	HTB7	43°57′52″N	86°30′27″E	950	45	QT5	43°43′53″N	89°33′44″E	1400
8	HTB8	43°56′54″N	86°28′24″E	1000	46	QT6	43°40′24″N	89°38′09″E	1500
9	HTB9	43°55′13″N	86°25′54″E	1100	47	QT7	43°39′12″N	89°37′31″E	1600
10	HTB10	43°53′43″N	86°24′24″E	1200	48	QT8	43°38′34″N	89°37′32″E	1650
11	HTB11	43°52′07″N	86°23′26″E	1300	49	QT9	43°38′15″N	89°36′57″E	1700
12	HTB12	43°50′39″N	86°22′36″E	1400	50	QT10	43°37′27″N	89°36′59″E	1750
13	HTB13	43°50′35″N	86°21′49″E	1500	51	QT11	43°37′04″N	89°36′51″E	1800
14	HTB14	43°50′30″N	86°21′01″E	1600	52	QT12	43°36′58″N	89°36′02″E	1850
15	HTB15	43°49′41″N	86°17′22″E	1650	53	QT13	43°35′56″N	89°36′50″E	1900
16	HTB16	43°49′37″N	86°17′27″E	1700	54	QT14	43°35′31″N	89°36′47″E	1950
17	HTB17	43°49′35″N	86°17′34″E	1750	55	QT15	43°34′36″N	89°36′50″E	2000
18	HTB18	43°47′36″N	86°19′37″E	1800	56	QT16	43°34′05″N	89°36′46″E	2050
19	HTB19	43°47′20″N	86°19′27″E	1850	57	QT17	43°33′42″N	89°36′43″E	2100
20	HTB20	43°47′07″N	86°19′16″E	1900	58	QT18	43°33′11″N	89°36′39″E	2150
21	HTB21	43°46′55″N	86°19′12″E	1950	59	QT19	43°32′42″N	89°36′39″E	2200
22	HTB22	43°46′54″N	86°19′16″E	2000	60	QT20	43°32′21″N	89°36′43″E	2250
23	HTB23	43°46′15″N	86°18′37″E	2050	61	QT21	43°32′04″N	89°36′40″E	2300
24	HTB24	43°46′01″N	86°18′36″E	2100	62	QT22	43°31′36″N	89°36′22″E	2350
25	HTB25	43°47′12″N	86°16′01″E	2150	63	QT23	43°31′20″N	89°36′16″E	2400
26	HTB26	43°47′08″N	86°15′53″E	2200	64	QT24	43°30′59″N	89°36′13″E	2450
27	HTB27	43°47′07″N	86°15′50″E	2250	65	QT25	43°30′41″N	89°36′10″E	2500
28	HTB28	43°44′01″N	86°20′27″E	2300	66	QT26	43°30′27″N	89°36′10″E	2525
29	HTB29	43°43′55″N	86°20′14″E	2350	67	QT27	43°30′35″N	89°36′16″E	2550
30	HTB30	43°43′48″N	86°19′59″E	2400	68	QT28	43°30′34″N	89°36′18″E	2575
31	HTB31	43°43′43″N	86°20′04″E	2450	69	QT29	43°30′34″N	89°36′20″E	2600
32	HTB32	43°43′44″N	86°20′06″E	2500	70	QT30	43°30′09″N	89°36′15″E	2625
33	HTB33	43°43′44″N	86°19′30″E	2525	71	QT31	43°30′02″N	89°36′11″E	2650
34	HTB34	43°43′42″N	86°19′20″E	2550	72	QT32	43°30′09″N	89°36′19″E	2675
35	HTB35	43°43′37″N	86°19′17″E	2575	73	QT33	43°29′58″N	89°36′13″E	2700
36	HTB36	43°43′36″N	86°19′17″E	2600	74	QT34	43°29′49″N	89°36′03″E	2725
37	HTB37	43°43′35″N	86°19′17″E	2625	75	QT35	43°29′45″N	89°36′04″E	2750
38	HTB38	43°43′32″N	86°19′17″E	2650					

Note: HTB, Hutubi County; QT, Qitai County.

3.2 Pollen analysis

Samples for pollen analysis were sequentially pre-treated using a modified HCL–NaOH–HF procedure (Fægri and Iversen, 1989) at the Institute of Hebei Normal University and the Key

Laboratory of Western China's Environmental System, Ministry of Education, Lanzhou University. Pollen identification was conducted at a magnification of ×400 under an optical microscope (Zeiss Imager A2, Carl Zeiss Microscopy GmbH, Jena, Germany) at Hebei Normal University. A minimum of 500 grains were counted for each sample, except for samples with extremely low abundance. The pollen percentage was obtained by dividing the number of pollen grains of a family genus by the total number of pollen grains, whereas the pollen concentration was obtained by multiplying the number of pollen grains of a family genus by the number of *Lycopodium* spores (10,315 grains) added, then dividing by the number of *Lycopodium* spores counted as well as the sample mass. Tilia 1.7.16 software was used to construct pollen percentage and pollen concentration diagrams.

3.3 Statistical analysis

To determine the representativeness of surface pollen, we chose pollen percentages of selected pollen types (all with a mean pollen content more than 2.00% and corresponding plant types occurring in multiple samples) and their vegetation cover. Next, we calculated the R-value associated with the vegetation distribution (R-value=P/V, where P is pollen percentage (%) and V is vegetation cover (%)) (Davis, 1963), and computed the average value based on data from many samples.

To explore the relationships between surface pollen assemblages and environmental factors in different vegetation zones, we conducted a detrended correspondence analysis using Canoco 5 software (ter Braak and Smilauer, 2012). The meteorological information of the sampling locations was obtained from the National Earth System Science Data Center (http://www.geodata.cn), and the average data of climate parameters (1981–2010) for each sampling location were obtained by extracting them using ArcGIS 10.2 software. In this study, a total of six meteorological parameters were selected: P_{ann}, T_{ann}, July mean temperature (T_{Jul}), January mean temperature (T_{Jan}), July mean precipitation (P_{Jul}), and January mean precipitation (P_{Jan}). In the ordination analysis, a total of 15 pollen taxa (average content ≥0.50%) was chosen as dataset, and P_{ann}, T_{ann}, T_{Jul}, T_{Jan}, P_{Jul}, P_{Jan}, and altitude were used as the environmental variables. The gradient length of the pollen percentage data determined by detrended correspondence analysis was short (standard deviation unit of turnover is 1.6). This indicates that the linear model-based RDA is suitable for evaluating the pollen–environment relationships and isolating the environmental factors that explain the most variation among the surface pollen assemblages.

4 Results

4.1 Characteristics of surface pollen assemblages in different vegetation zones

Our results indicated that the surface pollen assemblages in the vertical vegetation zones of HTB and QT were approximately the same. A total of 47 pollen and spore taxa were identified within the 75 samples, consisting of 13 tree, 4 shrub, 25 herb, and 5 fern taxa. A total of 39,539 pollen and spore grains were identified, with an average of 530 grains per sample. The average total pollen concentration of each sample was 15,110 grain/g. The pollen assemblages were dominated by herb pollen: HTB samples contained 57.99% herb pollen, and QT samples contained 59.35% herb pollen. Both regions were dominated by Chenopodiaceae (44.21% in HTB and 42.85% in QT), followed by *Artemisia* (9.63% in HTB and 6.69% in QT). Tree pollen content also accounted for a large proportion of the recorded pollen: *Picea* comprised 38.85% in HTB and 34.17% in QT. Shrub pollen content was low, represented largely by *Ephedra*. In addition, the *Artemisia*/Chenopodiaceae ratio (A/C) was used to characterize the drought degree of the mountain steppe and mountain desert zones, whereas the arboreal pollen/non-arboreal pollen ratio (AP/NAP) was used as an indicator of vegetation change. Based on the topographic and geomorphological features of the study area and relevant data from modern vegetation surveys, we divided the surface pollen data of HTB (Fig. 2) and QT (Fig. 3) into five pollen assemblage

zones, including Zone I (mountain desert zone), Zone II (mountain steppe zone), Zone III (mountain forest zone), Zone IV (subalpine meadow zone), and Zone V (alpine mat vegetation zone) according to altitude from low to high.

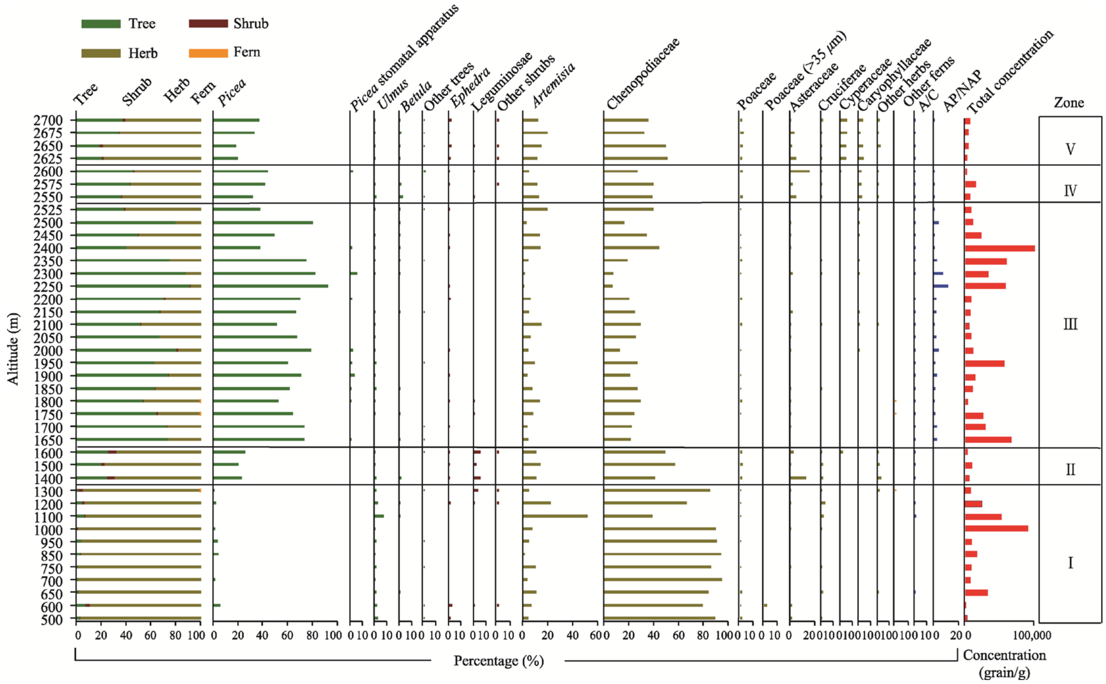

Fig. 2 Pollen percentage and concentration spectra of surface samples in the region of HTB on the northern slopes of the central Tianshan Mountains. A/C, *Artemisia*/Chenopodiaceae ratio; AP/NAP, arboreal pollen/non-arboreal pollen ratio; Zone I, mountain desert zone; Zone II, mountain steppe zone; Zone III, mountain forest zone; Zone IV, subalpine meadow zone; Zone V, alpine mat vegetation zone.

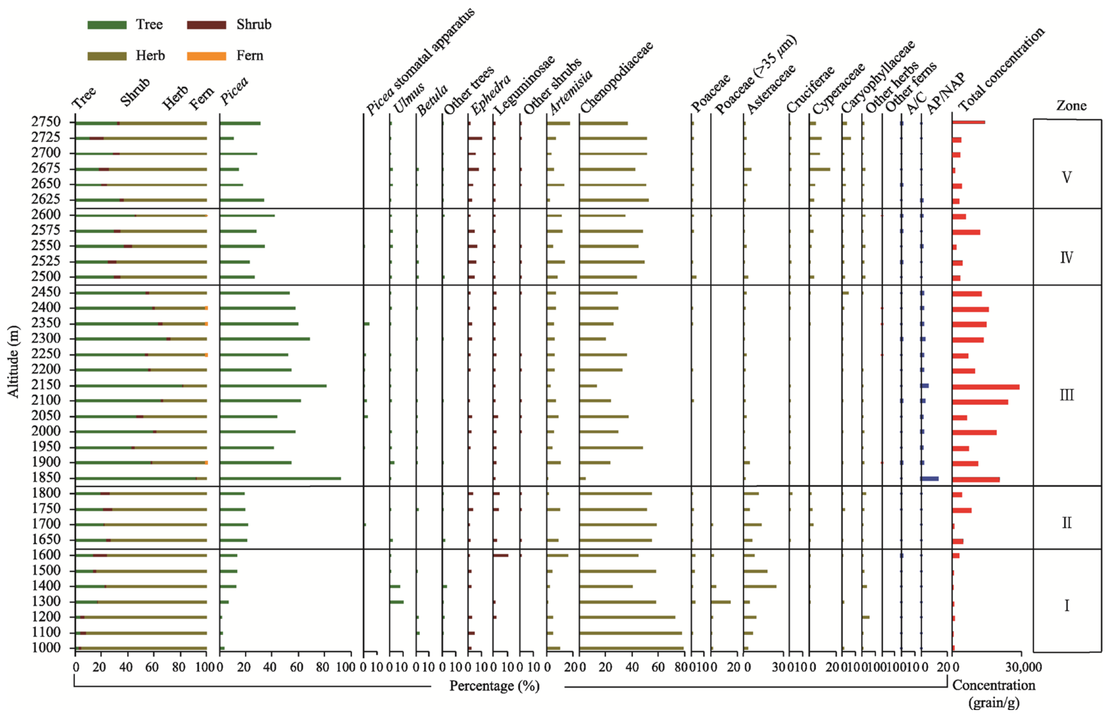

Fig. 3 Pollen percentage and concentration spectra of surface samples in the region of QT on the northern slopes of the eastern Tianshan Mountains

4.1.1 Zone I: mountain desert zone (Hutubi County (HTB): 500–1300 m; Qitai County (QT): 1000–1600 m)

The total pollen concentration in this vegetation zone was 14,550 grain/g. The percentage of tree pollen accounted for a small part, with an average of 3.92% in HTB and 11.58% in QT. These quantities represent the lowest values found throughout any of the vegetation zone. This region also had the lowest proportion of *Picea* at 1.83% in HTB and 7.53% in QT. *Ulmus* showed a peak value in this zone, with an average of 1.68% in HTB and 2.59% in QT. Shrubs were low in this region, averaging 1.05% in HTB and 3.61% in QT. The pollen dominance of herb plants was notable, with an average content of 94.99% in HTB and 84.79% in QT. Specific herb pollen contents were noteworthy for their abundance: Chenopodiaceae totaled 81.46% in HTB and 61.38% in QT. Moreover, the pollen contents of *Artemisia* (11.57% in HTB and 5.99% in QT) and Asteraceae (0.51% in HTB and 10.43% in QT) were also common. The AP/NAP (0.04 in HTB and 0.14 in QT) and A/C (0.21 in HTB and 0.08 in QT) were the lowest of any vegetation zone.

4.1.2 Zone II: mountain steppe zone (HTB: 1400–1600 m; QT: 1650–1800 m)

The total pollen concentration in this vegetation zone was significantly lower than that in Zone I, with an average of 5238 grain/g. Compared with Zone I, the tree content increased significantly in this zone, reaching 24.08% in HTB and 22.05% in QT. The pollen of *Picea* increased, whereas the pollen content of *Betula* and *Ulmus* decreased. Shrub pollen content was slightly higher than that in Zone I, with an average of 5.16% in HTB and 4.61% in QT. The pollen content of Leguminosae reached its acme in this zone, at 4.47% in HTB and 2.13% in QT. Herb plant pollen dominated, but the content decreased slightly compared with that in Zone I. The herb pollen averaged 70.76% in HTB and 73.33% in QT. The pollen content of Chenopodiaceae decreased most notably, with an average content of 49.11% in HTB and 54.85% in QT. An increase in the pollen of Poaceae was present (1.06% in HTB and 1.41% in QT), and smaller changes in *Artemisia* (11.68% in HTB and 4.98% in QT). Compared with Zone I, the AP/NAP (0.32 in HTB and 0.29 in QT) and A/C (0.24 in HTB and 0.10 in QT) increased significantly.

4.1.3 Zone III: Mountain forest zone (HTB: 1650–2525 m; QT: 1850–2450 m)

The total pollen concentration in this vegetation zone was the highest among all zones, with an average of 24,156 grain/g. Tree pollen content reached its highest value, averaging 67.16% in HTB and 61.93% in QT. *Picea* pollen averaged 65.21% in HTB and 59.64% in QT. The *Picea* stomatal apparatus (1.08% in HTB and 0.84% in QT) and AP/NAP (2.95 in HTB and 2.50 in QT) also reached the highest values among all vegetation zones. Shrub pollen content decreased to its lowest values, with an average of 0.53% in HTB and 2.28% in QT. Compared with Zone II, the herb pollen content decreased, falling to its lowest values, and averaging at 32.29% in HTB and 35.73% in QT. Moreover, all herb pollen showed different degrees of decline compared with Zone II. The pollen contents of Chenopodiaceae (23.72% in HTB and 26.83% in QT), Asteraceae (0.56% in HTB and 1.19% in QT), *Artemisia* (7.23% in HTB and 5.75% in QT), and Poaceae (0.25% in HTB and 0.50% in QT) all markedly decreased. Compared with Zone II, the A/C increased to their highest values (0.28 in HTB and 0.23 in QT).

4.1.4 Zone IV: subalpine meadow zone (HTB: 2550–2600 m; QT: 2500–2600 m)

Compared with Zone III, the total pollen concentration in this vegetation zone decreased considerably, with an average of 7896 grain/g. A significant decrease in the amount of tree pollen compared with Zone III was present due to the decrease in *Picea* pollen, which accounted for 38.91% in HTB and 30.50% in QT. The *Picea* content decreased markedly with increasing altitude. The content of shrub pollen (1.26% in HTB and 5.03% in QT) was substantially higher than in Zone III. *Ephedra* and Leguminosae were commonly occurring shrubs. The herb pollen content increased notably compared with that in Zone III, averaging 56.61% in HTB and 61.22% in QT. Among the herbs, Chenopodiaceae (35.31% in HTB and 43.83% in QT), *Artemisia* (9.56% in HTB and 9.93% in QT), Asteraceae (7.22% in HTB and 1.21% in QT), and Cyperaceae (0.46%

in HTB and 1.72% in QT) showed varying degrees of increase. The AP/NAP (0.74 in HTB and 0.53 in QT) and A/C (0.26 in HTB and 0.22 in QT) decreased slightly compared with those in Zone III.

4.1.5 Zone V: alpine mat vegetation zone (HTB: 2625–2700 m; QT: 2625–2750 m)

The total pollen concentration in this vegetation zone was the lowest among all zones, with an average of 5007 grain/g. Compared with Zone IV, the tree pollen content continued to decrease, dominated by the decline in *Picea* pollen (26.86% in HTB and 22.53% in QT). The pollen content of shrub plants was substantially higher than in Zone IV, with an average content of 1.93% in HTB and 5.56% in QT. The pollen content of *Ephedra* (1.47% in HTB and 4.90% in QT) reached its highest value in this zone. The pollen content of herb plants continued to increase compared with Zone IV, with an average of 69.72% in HTB and 69.96% in QT. Among the herbs, Chenopodiaceae (42.04% in HTB and 47.12% in QT) and *Artemisia* (14.16% in HTB and 7.98% in QT) pollen contents increased markedly. Moreover, many herb pollen types, including Poaceae, Cyperaceae, and Caryophyllaceae, reached their highest values. The AP/NAP (0.41 in HTB and 0.34 in QT) and A/C (0.25 in HTB and 0.18 in QT) continued to decline compared with those in Zone IV.

4.2 Redundancy analysis (RDA) results

From RDA (Fig. 4), the eigenvalues of the first and second axes were 0.294 and 0.134, respectively, and species–environment correlations reached 0.913 and 0.824. Environmental factors represented by Axis 1 and Axis 2 are the major factors that affected the surface pollen assemblage in the study area, which accounted for 57.22% and 26.02% of the total variance, respectively. In the RDA ordination diagram, black arrows represent species variables and red arrows represent environmental factors; the directions and angles of the red arrows with the ordination axis, and the length of the vertical direction indicate the degree of correlation between the environmental factors and the ordination axis. According to Figure 4, all environmental factors were highly correlated with the first axis and less correlated with the second axis. Among them, P_{ann}, P_{Jul}, T_{Jan}, and altitude were related with the negative half-axis of Axis 1, whereas T_{ann}, P_{Jan}, and T_{Jul} are correlated with the positive half-axis of Axis 1.

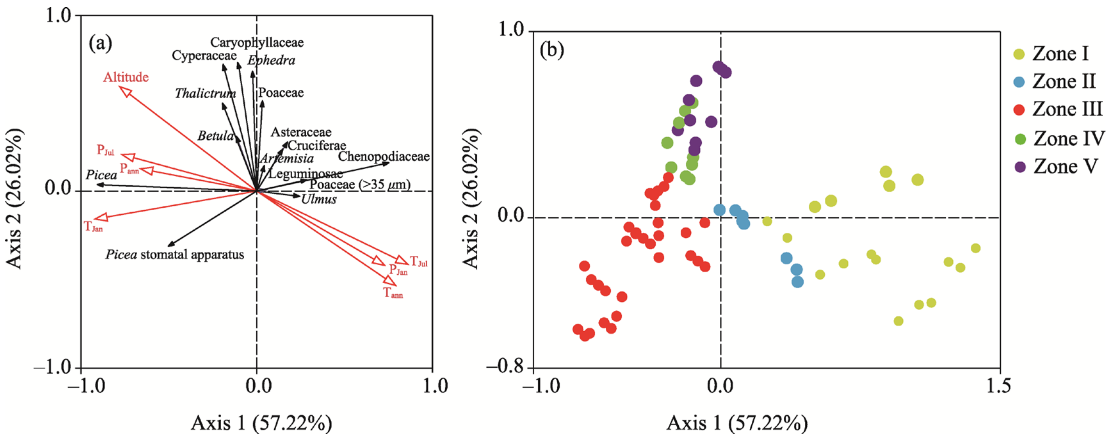

Fig. 4 Redundancy analysis of pollen samples and environmental factors in the study area. P_{ann}, average annual precipitation; T_{ann}, annual average temperature; T_{Jul}, July mean temperature; T_{Jan}, January mean temperature; P_{Jul}, July mean precipitation; P_{Jan}, January mean precipitation.

5 Discussion

5.1 Relationship between surface pollen assemblages and modern vegetation on the northern slopes of the Tianshan Mountains

The mountain desert zone is in the lowlands of the northern slopes of the mountains. This

vegetation zone has low humidity, few species, low vegetation cover, and a wide distribution of Chenopodiaceae desert, mainly including Asteraceae, *Artemisia*, and Chenopodiaceae, such as *C. arenarius* and *S. borotalense*. The surface pollen assemblages are dominated by Chenopodiaceae pollen, with smalls proportions of *Artemisia* and Asteraceae as well as Leguminosae, *Ulmus*, and *Picea* pollen. Because mature spruce and elm are not found around the sampling sites, the presence of *Picea* pollen may be a result of the valley wind, which transports pollen from higher altitudes (Wang et al., 2017; Yang et al., 2019); the presence of *Ulmus* pollen may originate from the elm trees that line the village and road (Lang et al., 2020). In general, the pollen assemblages are dominated by desert vegetation pollen and are relatively stable. The pollen combination dominated by Chenopodiaceae, *Artemisia*, and Asteraceae roughly equates to the distribution of local vegetation, and is similar to the results of surface pollen assemblages in other areas of the Tianshan Mountains (Yang et al., 2016; Yao et al., 2021b).

The humidity in the mountain steppe zone gradually increases, and Chenopodiaceae and *Artemisia* remain the major plants; Poaceae plants increase significantly, with various *Stipa* plants appearing, accompanied by some Asteraceae plants and Leguminosae shrubs. *Populus* and *Betula* plants are also distributed near the river floodplain owing to the high water table. Chenopodiaceae pollen remains dominant in the surface pollen assemblages, and *Artemisia* pollen content displays no significant change because of grassland degradation caused by overgrazing (Liu et al., 2006; Wei and Zhao, 2016; Zhao et al., 2019). Although, *Artemisia* pollen occupied a large proportion (approximately 30.00%) of the mountain steppe zone in previous studies (Lang et al., 2020; Yao et al., 2021a). Poaceae pollen increases slightly, but markedly less than the corresponding increase in vegetation cover; this could be related to the under-representation of Poaceae (Chen et al., 2021a; Zhao et al., 2021) or anthropogenic disturbances, such as overcultivation and overgrazing (Ma et al., 2008; Wei and Zhao, 2016). The combination of Chenopodiaceae, *Picea*, *Artemisia*, and Asteraceae dominating the pollen pattern in the mountain steppe zone is slightly different from the local vegetation distribution. This variation may be influenced by the low representation of Poaceae, exotic *Picea* pollen, and anthropogenic activities.

The humidity in the mountain forest zone continues to increase, with spruce forests as the constructive species and mixed forests of spruce with poplar and birch growing in specific areas. Shrub plants are also common, mainly grasses under the forest. In addition, meadow vegetation occurs on the shady slopes of mountains at higher altitudes and on the moist areas adjacent to rivers. The pollen dominance of *Picea* in this vegetation zone is notable, averaging over 60.00%, with the highest at 92.00%. The average AP/NAP (2.95 in HTB and 2.50 in QT) of *Picea* pollen is higher, and *Picea* stomatal apparatus is widespread. Stomata are from whole leaves or fragments of large leaves and their guard cells are lignified; these are durable and easily preserved in stratigraphic deposits, and the stomata of pollen can indicate the presence of parent plants (Li et al., 2017). Therefore, the extensive presence of stomatal apparatus of *Picea* pollen in this zone is likely related to the arboreal vegetation zone (Wei and Zhao, 2016). This phenomenon has a certain vegetation indication significance, and provides an important basis for vegetation reconstruction using *Picea* pollen on the northern slopes of the Tianshan Mountains (Zhang et al., 2006; Li et al., 2021). The higher levels of Chenopodiaceae and *Artemisia* pollen do not correspond to vegetation cover and are therefore likely exogenous pollen (Yang et al., 2019; Li et al., 2021). The surface pollen assemblage in the study area is represented by *Picea*, Chenopodiaceae, and *Artemisia*, which generally mirrors the modern vegetation distribution. Compared with other research results on the northern slopes of the Tianshan Mountains, the species diversity in this area is scarce, with the average pollen content of *Picea* exceeding 60.00%, and other shrubs and herbs have fewer pollen types. In contrast, the western region of the Tianshan Mountains (Yang et al., 2019; Yao et al., 2021b) displays a higher species diversity, and pollen grains from associated herbs and shrubs are well represented, which may be related to the climatic characteristics of the northern slopes of the Tianshan Mountains showing a gradual increase in drought from west to east (Yao et al., 2021b).

The subalpine meadow zone is distributed across the shady slopes of valleys above the

mountain forest zone, where the spruce forest disappears and communities with meadow plants as the dominant species appear. The meadow plants are primarily *K. capillifolia*, *K. myosuroides*, *D. glomerata*, and *P. viviparum*. However, the pollen assemblage continues to display Chenopodiaceae, *Picea*, *Artemisia*, and Asteraceae. There is a subtle increase in the pollen of wet plant Cyperaceae, which may be related to the under-representation of Cyperaceae pollen (Chen et al., 2021a; Zhao et al., 2021). The pollen assemblages of subalpine meadows in the arid areas remain dominated by desert plants with large pollen yields that spread with comparative ease, and are similar to the results of surface pollen assemblages in other areas of the Tianshan Mountains (Li et al., 2017; Yao et al., 2021a). The prevalence of these desert plants reflects the influence of moisture on the distribution of vegetation in arid areas.

The alpine mat vegetation zone belongs to the alpine climate zone, with sparse vegetation growth and low vegetation cover, mainly including Rosaceae plants, such as *S. tetrandra* and *P. biflora*. The pollen assemblages contain Chenopodiaceae, *Picea*, *Artemisia*, and Cyperaceae, with considerable differences from the local vegetation distribution. Pollen from middle and low mountain steppe and desert vegetation zones, such as Chenopodiaceae and *Artemisia*, is abundantly distributed here as exotic pollen (Wei and Zhao, 2016). Airborne *Picea* pollen is also present in this zone (Yao et al., 2021a), which is common throughout the Tianshan Mountains and is thought to be influenced by atmospheric circulation systems (Luo et al., 2010; Ma et al., 2017). This phenomenon highlights the need for caution in conducting paleoenvironmental evolution studies in this region, to avoid miscalculations caused by exotic pollen.

5.2 Relationships between vertical vegetation zones and environmental factors on the northern slopes of the Tianshan Mountains

The general trends in precipitation and temperature with changing altitude in mountainous areas are as follows: precipitation increases with altitude and then gradually decreases after a certain altitude; and temperature decreases with altitude. The Tianshan Mountains are located deep within the interior of the continent, and moisture is primarily carried by the prevailing westerly winds (Zhang et al., 2022). The temperature drops under the effect of topographic uplift and water vapor in the atmosphere condenses, thus forming precipitation. Research has shown that the precipitation in the Tianshan Mountains first increases and then decreases with altitude, and an altitude of approximately 3500 m represents the maximum precipitation altitude zone (Ning, 2013). In this study, the altitude increased from 500 to 2750 m, which represented the mountain desert zone to alpine mat vegetation zone. As altitude increased, P_{ann} gradually increased, and T_{ann} gradually decreased, reflecting the gradient change of P_{ann} and T_{ann}. According to the RDA results (Fig. 4), P_{ann} and P_{Jul} are correlated with the negative portion of the Axis 1, and T_{ann} and T_{Jul} are correlated with the positive portion of the Axis 1; this result suggests that P_{ann} and T_{ann} have a significant effect on surface pollen assemblages. Moreover, the angle between P_{ann} and the Axis 1 is the smallest (Fig. 4), which may imply that P_{ann} is the main factor affecting the distribution of surface pollen in the study area, which is consistent with the results of studies in other regions (Li et al., 2011a, b; Wei and Zhao, 2016; Li et al., 2017; Yang et al., 2019); thus, providing a basis for reconstructing the paleovegetation and paleoclimate using fossil pollen assemblages in this area.

Picea, Cyperaceae, and Caryophyllaceae pollen all show high correlations with P_{ann} and P_{Jul}, and *Picea* pollen also shows a high correlation with T_{Jan} (Fig. 4). These percentage of pollen contents gradually increase as humidity increases at higher altitudes. These plant species prefer wet growth and generally grow in wetter areas at high altitudes, influenced by altitude and precipitation; this is consistent with the results of previous studies (Zhao and Li, 2013; Niu et al., 2022) and the physiological characteristics of these plants. *Picea* pollen reaches its acme in the forest zone, whereas Cyperaceae and Caryophyllaceae pollen attain their acme in the subalpine meadow zone and alpine mat vegetation zone. Among the arbor plant species, spruce, as the main constructive tree species in the coniferous forest, represents the coldest climatic environment (Yang et al., 2019), and is often distributed as patchy forests on shady and semi-shady slopes. Cyperaceae is a product of a cold and wet climate, indicating a wetter ecological environment

than that of the steppe (Yao et al., 2021a). This plant is mostly distributed across the alpine meadow belt on the shady slopes of valleys with high environmental humidity (Ma et al., 2017). Chenopodiaceae pollen shows a significant negative correlation with P_{ann}, and a significant positive correlation with T_{ann}, T_{Jul}, and P_{Jan}. The percentage of Chenopodiaceae pollen is the highest in the mountain steppe zone and mountain desert zone that have less precipitation and high temperature. Chenopodiaceae plants have characterized the arid climatic environment since the onset of the Quaternary period (Sun et al., 2010). Previous work in the northern Xinjiang and Hongshanzui area of the Altay Mountains similarly concluded that Chenopodiaceae was positively correlated with precipitation and negatively correlated with temperature (Wu et al., 2018; Li et al., 2021).

The pollen types in the samples from vegetation Zone I and Zone II are mainly Chenopodiaceae and show a significant positive correlation with T_{ann}, and especially T_{Jul} (Fig. 4), representing conditions of the desert vegetation zone. The samples from vegetation Zone III show a significant negative correlation with T_{ann}, but a positive correlation with P_{ann}, and especially P_{Jul} (Fig. 4), indicating that they are considerably affected by P_{ann}, and especially P_{Jul}, which corresponds well to the forest zone from which these samples were harvested. The samples from vegetation Zone IV and Zone V are highly affected by P_{ann} (Fig. 4), which corresponds to the alpine mat and subalpine meadow vegetation zones from which they were harvested. Moreover, in addition to the effects of temperature and precipitation on surface pollen distribution in the study area, there are also studies showing the effects of wind, wind speed, and mountain slope on surface pollen distribution (Wang et al., 2017; Lang et al., 2020; Zhao et al., 2020). These phenomena are also evident in the study area; for example, *Picea* pollen still comprises a high proportion of the pollen in the subalpine meadow and alpine mat vegetation zones above the altitude of the forest zone. This result may be explained by the influence of westerly circulation in the study area, where *Picea* pollen is blown to higher altitudes under the combined effect of westerly airflow and updrafts from the valleys and mountainous windward slopes (Lang et al., 2020). However, in general, the relationships between modern pollen assemblages and climatic factors essentially match the distributions observed in actual vegetation zones, which provides a certain reference for the application of fossil pollen assemblages of vertical vegetation zones in the region to reconstruct paleovegetation and paleoclimate.

5.3 Relationship between the percentage of dominant pollen types and vegetation cover on the northern slopes of the Tianshan Mountains

Our results show that *Picea*, *Artemisia*, Chenopodiaceae, and Asteraceae pollen contents are notable (average pollen content >2.00%) in the surface pollen assemblages of the vertical vegetation zones. Moreover, the corresponding plant types occur in several samples. Therefore, they can be regarded as important components for paleovegetation reconstruction. We analyzed the percentages of these four dominant pollen types and their altitude-induced vegetation cover variation characteristics (Fig. 5). In addition, we also analyzed the *R*-value of the main pollen types and the correlation between pollen percentage and their vegetation cover (Fig. 6).

5.3.1 *Picea* pollen

The vegetation cover of spruce plants is highly variable in different vegetation zones. In all zones except for the spruce forest, there is no apparent spruce vegetation cover (Fig. 5a and e). The vegetation cover of *Picea* plants in the spruce forest is high, averaging 38.00%, whereas the pollen percentage averages 62.45% (Fig. 5a and e). Moreover, the percentage of *Picea* pollen still accounts for 17.07% in the absence of spruce vegetation cover, and the *R*-value of *Picea* pollen is 1.61 (Fig. 6a), which indicate that *Picea* pollen is over-represented. These results are similar to those of previous research (Wei and Zhao, 2016; Yang et al., 2016). When the vegetation cover of spruce ranges between 30.00% and 40.00%, the pollen percentage of *Picea* is higher than 50.00%, averaging at 59.05%. When the spruce vegetation cover exceeds 40.00%, the average *Picea* pollen percentage is 65.08%. Therefore, a significant correlation exists between the percentage of *Picea* pollen and vegetation cover, with a correlation coefficient of 0.86 (Fig. 6a). Chen et al.

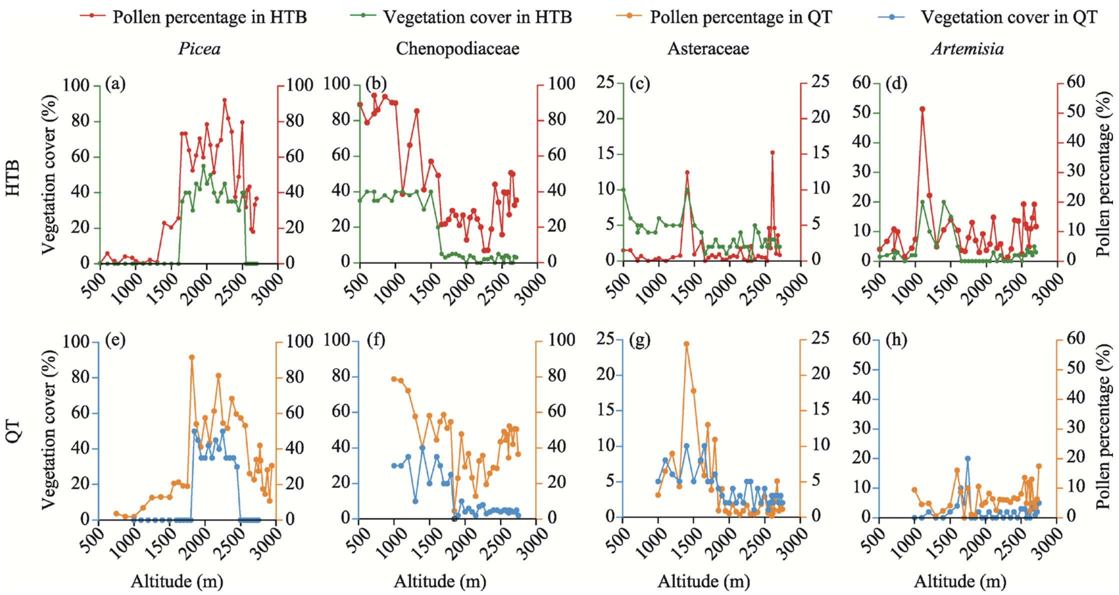

Fig. 5 Characteristics of vegetation cover and pollen percentage changes of dominant pollen types in the regions of HTB (a–d) and QT (e–h) under different altitude conditions

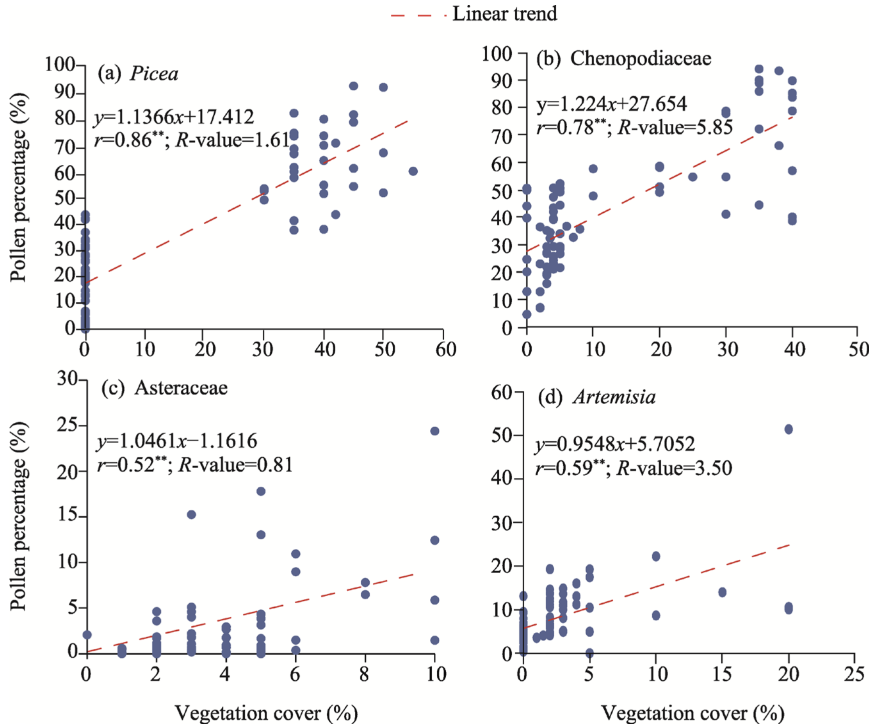

Fig. 6 Scatter plots of the relationships between the pollen percentage of dominant pollen types and their vegetation cover. (a), *Picea*; (b), Chenopodiaceae; (c), Asteraceae; (d), *Artemisia*. *R*-value is the representativeness of dominant pollen types, and ** indicates significant correlation at the 0.01 level.

(2021a) showed that the percentage of *Picea* pollen was significantly higher than the vegetation cover, and the *R*-value was higher than 1.00, which also reflected the over-representation of *Picea* pollen. The study of surface pollen in northern China showed that a higher vegetation cover of *Picea* equated to a greater percentage of *Picea* pollen, with the correlation coefficient reaching 0.94 (Xu et al., 2007).

5.3.2 Chenopodiaceae pollen

The vegetation cover of Chenopodiaceae pollen plants varies greatly between different vertical vegetation zones, though they are mainly concentrated in the mountain desert zone and mountain steppe zone (Fig. 5b and f). In other vegetation zones, the proportion of Chenopodiaceae plants is relatively low. Chenopodiaceae pollen is the most abundant pollen type in the pollen assemblages, and the overall percentage of Chenopodiaceae pollen is significantly correlated with vegetation cover, with correlation coefficients of up to 0.78 (Fig. 6b). The average vegetation cover of Chenopodiaceae plants is 13.00%, but its average pollen percentage is 43.60% (Fig. 5b and f), and the *R*-value of Chenopodiaceae pollen is greater than 1.00 (Fig. 6b); this result indicates that it is over-represented, a finding similar to the results of previous studies (Luo et al., 2009; Yao et al., 2021a). When the cover of Chenopodiaceae plants is less than 10.00%, the percentage of pollen still exceeds 20.00%, but is generally below 50.00%, averaging at 31.20%. When the cover of Chenopodiaceae plants is 10.00%–30.00%, the percentage of Chenopodiaceae pollen mostly exceeds 50.00%, averaging at 57.32%. When the Chenopodiaceae cover is higher than 30.00%, the pollen percentage is greater than 60.00%, with a peak value of 94.22%, averaging at 71.72%. Overall, Chenopodiaceae pollen increases with increasing vegetation cover. Through the study of surface pollen in the Qaidam Basin of China, Zhao et al. (2020) showed that when the vegetation cover of Chenopodiaceae was close to 0.00%, the percentage of Chenopodiaceae pollen still reached 10.20%–55.00%, and the *R*-value was generally greater than 1.00, which indicated over-representation. From a surface pollen study of the Bashang typical steppe region in northern China, Zhao et al. (2022) showed that the percentage of Chenopodiaceae pollen was significantly positively correlated with vegetation cover.

5.3.3 Asteraceae pollen

Asteraceae pollen is present in most of the samples in small proportions (below 10.00%). Asteraceae plants are also present at most of the sample sites (Fig. 5c and g); therefore, Asteraceae plants are the most common species in the community, but rarely become dominant or constructive species. Therefore, the cover of Asteraceae plants is mostly between 2.00% and 10.00%. When the cover of Asteraceae plants is less than 2.00%, the pollen content of Asteraceae is less than 1.00%; when the cover is 2.00%–5.00%, the pollen percentage increases, reaching 2.60% on average; and when the cover is higher than 5.00%, the pollen percentage increases with increasing cover, reaching an average of 8.02% (Fig. 5c and g). The *R*-value of Asteraceae pollen is close to 1.00 (Fig. 6c), which indicates that Asteraceae pollen can represent vegetation, and the percentage content of Asteraceae pollen roughly reflects its distribution in local vegetation, which is consistent with previous studies (Zhao et al., 2019; Chen et al., 2021a). Moreover, the correlation between the pollen percentage of Asteraceae and vegetation cover is also significant, with an overall correlation coefficient of 0.52 (Fig. 6c). Zhao et al. (2020) showed that in the Qaidam Basin of China there was a high correlation between Asteraceae pollen percentage and vegetation cover, with a correlation coefficient of 0.46. From a surface pollen study of the Bashang typical steppe region in northern China, Zhao et al. (2022) showed that the percentage of Asteraceae pollen increased slightly with an increase in vegetation cover; there was also a significant correlation between the pollen percentage and vegetation cover, with a correlation coefficient of 0.27.

5.3.4 *Artemisia* pollen

The distribution of *Artemisia* pollen resembles that of Chenopodiaceae, concentrated mainly in the mountain desert zone and mountain steppe zone at lower altitudes (Fig. 5d and h). The overall pollen percentage of *Artemisia* is significantly correlated with vegetation cover, with correlation coefficients up to 0.59 (Fig. 6d). The average cover of *Artemisia* species in the sampling areas is approximately 2.00%, but the average percentage of pollen is 8.52% (Fig. 5d and h), and the *R*-values of *Artemisia* pollen are greater than 1.00 (Fig. 6d); this result indicates an over-representation, which is similar to the results of previous studies (Chen et al., 2021a; Yao et

al., 2021a). The percentage of *Artemisia* pollen reaches approximately 5.00% when there is no vegetative cover of *Artemisia* plants; an average of approximately 10.00% when the cover of *Artemisia* plants is less than 5.00%; and approximately 20.00% when the cover of *Artemisia* plants is higher than 5.00%. Overall, the percentage of *Artemisia* pollen increases with increasing vegetation cover. Through a study around Balikun Lake in the eastern Tianshan Mountains, Zhao et al. (2021) showed that when the vegetation cover of *Artemisia* was low (<5.00%), the proportion of *Artemisia* pollen reached an average of approximately 10.00%, indicating over-represented pollen. This result is in accordance with Xu et al. (2007), who found a weak relationship between *Artemisia* pollen percentage and vegetation cover in northern China. When there were no *Artemisia* plants around the sampling sites, the average percentage of *Artemisia* pollen remained close to 20.00%, showing the over-representation of *Artemisia* pollen (Xu et al., 2007).

6 Conclusions

The qualitative analysis of pollen assemblages allows for the identification of different vegetation types. Surface pollen assemblages correspond well to modern vegetation distributions on the northern slopes of the Tianshan Mountains, when excluding the influence of Chenopodiaceae and *Artemisia* pollen on pollen assemblages in higher altitude vegetation zones and *Picea* pollen on pollen assemblages in non-forest zones. RDA result shows that P_{ann} and T_{ann} affect the distribution of surface pollen assemblages. Moreover, P_{ann} is the primary environmental factor affecting surface pollen assemblages in this region. *Picea*, Cyperaceae, and Caryophyllaceae pollen show significant positive correlations with P_{ann} and P_{Jul}, and Chenopodiaceae pollen shows significant positive correlations with T_{ann} and T_{Jul}. The pollen percentages of the four dominant pollen types (*Picea*, *Artemisia*, Chenopodiaceae, and Asteraceae) are significantly correlated with vegetation cover at the 0.01 significance level. The correlations between *Picea* and Chenopodiaceae pollen and vegetation cover are relatively high (approximately 0.80), whereas those between *Artemisia* and Asteraceae pollen and vegetation cover are relatively low (<0.60). In addition, *Picea*, *Artemisia*, and Chenopodiaceae pollen are over-represented, whereas Asteraceae pollen is well represented for vegetation.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (42071102).

References

Chen C Z, Huang X Z, Peng W, et al. 2012. Study of the surface sporopollen in the Small Yourdusi Basin on the southern slopes of the Tianshan Mountains. Journal of Glaciology and Geocryology, 34(6): 1526–1534. (in Chinese)

Chen L X, Li Y Y, Zhang Y, et al. 2021a. Relationship between surface pollen and modern vegetation in northern Xinjiang, China: Implications for paleovegetation and paleoclimate reconstruction. Quaternary International, 589: 124–134.

Chen L X, Zhang Y, Kong Z C. 2021b. Airborne pollen patterns and their relationship with meteorological factors in the *Betula* microphylla-dominated wetland of Ebinur Lake, Xinjiang, China. Science China Earth Sciences, 64: 1746–1760.

Chevalier M, Davis B A S, Heiri O, et al. 2020. Pollen-based climate reconstruction techiques for late Quaternary studies. Earth-Science Reviews, 210: 103384, doi: 10.1016/j.earscirev.2020.103384.

Comprehensive Investigation Team of Xinjiang and Institute of Botany, Chinese Academy of Sciences. 1978. Xinjiang Vegetation and its Utilization. Beijing: Science Press, 378. (in Chinese)

Davies C P, Fall P L. 2001. Modern pollen precipitation from an elevational transect in central Jordan and its relationship to vegetation. Journal of Biogeography, 28(10): 1195–1210.

Davis M B, 1963. On the theory of pollen analysis. American Journal of Science, 261(10): 897–912.

Deng W, Dai E F, Jia Y W, et al. 2015. Spatiotemporal coupling characteristics, effects and their regulation of water and soil elements in mountainous area. Mountain Research, 33(5): 513–520. (in Chinese)

Fægri K, Iversen J. 1989. Textbook of Pollen Analysis. Oxford: Blackwell.

Feng Y Y, Zhao Y L, Yang Z M, et al. 2021. Spatio-temporal differentiation of trade-offs and synergies of ecosystem services in

typical mountain areas of China. Journal of Resources and Ecology, 12(2): 268–279.

Ge Y W, Li Y C, Bunting M J, et al. 2017. Relation between modern pollen rain, vegetation and climate in northern China: implications for quantitative vegetation reconstruction in a steppe environment. Science of the Total Environment, 586: 25–41.

Ge Y W, Zhang K, Yang X D, et al. 2020. Pollen-vegetation/land use relationships in southeastern China: complexity and applicability for paleoenvironmental reconstruction. Ecological Indicators, 116: 106523, doi: 10.1016/j.ecolind.2020.106523.

Hou X Y. 2001. Vegetation Atlas of China (1: 1000000). Beijing: Science Press. (in Chinese)

Hu R J. 2004. Physical geography of the Tianshan Mountains in China. Beijing: China Environmental Science Press. (in Chinese)

Huang X Z, Chen X M, Du X. 2018. Modern pollen assemblages from human-influenced vegetation in northwestern China and their relationship with vegetation and climate. Vegetation History and Archaeobotany, 27: 767–780.

Lang Q, Yao F L, Yang H J. 2020. Surface pollen spectrum in intermountain basin of Middle Tianshan, Xinjiang, China. Chinese Journal of Ecology, 39(8): 2518–2527. (in Chinese)

Li F R, Zhao Y, Gaillard M J, et al. 2017. Modern pollen-climate relationships in north Xinjiang, northwestern China: Implications for pollen-based reconstruction of Holocene climate. The Holocene, 27(7): 951–966.

Li F R, Gaillard M J, Cao X Y, et al. 2020. Towards quantification of Holocene anthropogenic land-cover change in temperate China: A review in the light of pollen-based REVEALS reconstructions of regional plant cover. Earth-Science Reviews, 203: 103119, doi: 10.1016/j.earscirev.2020.103119.

Li X Q, Zhao K L, John D, et al. 2011a. Moisture dynamics in central Asia for the last 15 kyr: new evidence from Yili Valley, Xinjiang, NW China. Quaternary Science Reviews, 30(23–24): 3457–3466.

Li Y C, Bunting M J, Xu Q H, et al. 2011b. Pollen-vegetation-climate relationships in some desert and desert steppe communities in Northern China. The Holocene, 21(6): 997–1010.

Li Y C, Ge Y W, Bunting M J, et al. 2017. Relative pollen productivities and relevant source area of pollen in the forest-steppe ecotone of northern China. Review of Palaeobotany and Palynology, 244: 1–12.

Li Y F, Li C H, Xu L Y, et al. 2017. Relationships between vegetation and stomata, and between vegetation and pollen surface soil in Taibai Mountains. Acta Palaeontologica Sinica, 56(1): 108–116. (in Chinese)

Li Y Y, Zhang Y, Kong Z C, et al. 2021. Surface sporopollen and modern vegetation in Hongshanzui area Altai, Xinjiang, China. Chinese Journal of Plant Ecology, 45(2): 174–186. (in Chinese)

Liu H Y, Wang Y, Tian Y H, et al. 2006. Climatic and anthropogenic control of surface pollen assemblages in East Asian steppes. Review of Palaeobotany and Palynology, 138(3–4): 281–289.

Long H, Shen J, Chen J H, et al. 2017. Holocene moisture variations over the arid central Asia revealed by a comprehensive sand-dune record from the central Tian Shan, NW China. Quaternary Science Reviews, 174: 13–32.

Lu H Y, Wu N Q, Liu K B, et al. 2011. Modern pollen distributions in Qinghai-Tibetan Plateau and the development of transfer functions for reconstructing Holocene environmental changes. Quaternary Science Reviews, 30(7–8): 947–966.

Luo C X, Zheng Z, Tarasov P, et al. 2009. Characteristics of the modern pollen distribution and their relationship to vegetation in the Xinjiang region, northwestern China. Review of Palaeobotany and Palynology, 153(3–4): 282–295.

Luo C X, Zheng Z, Tarasov P. 2010. A potential of pollen-based climate reconstruction using a modern pollen-climate dataset from arid northern and western China. Review of Palaeobotany and Palynology, 160(3–4): 111–125.

Ma Q F, Zhu L P, Wang J B, et al. 2017. *Artemisia*/Chenopodiaceae ratio from surface lake sediments on the central and western Tibetan Plateau and its application. Palaeogeography, Palaeoclimatology, Palaeoecology, 479: 138–145.

Ma Y Z, Liu K B, Feng Z D, et al. 2008. A survey of modern pollen and vegetation along a south-north transect in Mongolia. Journal of Biogeography, 35(8): 1512–1532.

Ning L K. 2013. Study on the influence of topography and geomorphology on precipitation over Tianshan Mountains, Central Asia. MSc Thesis. Shihezi: Shihezi University. (in Chinese)

Niu D Y, Li J Y, Wang N L, et al. 2022. Relationship between pollen assemblages in surface soil and modern vegetation and climate in the western Tianshan Mountains, Xinjiang. Journal of Glaciology and Geocryology, 44(3): 1070–1082. (in Chinese)

Pan Y F, Yan S, Behling H, et al. 2013. Transport of airborne *Picea schrenkiana* pollen on the northern slope of Tianshan Mountains (Xinjiang, China) and its implication for paleoenvironmental reconstruction. Aerobiologia, 29(2): 161–173.

Ran M, Zhang C J, Feng Z D. 2015. Climatic and hydrological variations during the past 8000 years in northern Xinjiang of China and the associated mechanisms. Quaternary International, 358: 21–34.

Sun F F, Zhang W Y, Gong J C, et al. 2010. The palaeoenvironmental reconstruction on pollen proxy in the Qaidam Basin since Late Pliocene. Geological Review, 56(5): 621–628. (in Chinese)

ter Braak C J F, Smilauer P. 2012. CANOCO Reference Manual and User's Guide: Software for Ordination (Version 5). Ithaca: Microcomputer Power.

Wang L, Zhang Y, Kong Z C, et al. 2017. Preliminary study on pollen distribution in the surface soil of the Turpan region in the

southern slope of Tianshan Mountains, Xinjiang, China. Chinese Journal of Plant Ecology, 41(7): 779–786. (in Chinese)

Wei H C, Zhao Y. 2016. Surface pollen and its relationships with modern vegetation and climate in the Tianshan Mountains, northwestern China. Vegetation History and Archaeobotany, 25(1): 19–27.

Wu H X, Xu H, Lan J H, et al. 2018. Pollen assemblages in surface soil and their relationships with vegetation and climate in northern Xinjiang. Chinese Journal of Ecology, 37(12): 3499–3507. (in Chinese)

Xu Q H, Li Y C, Li Y, et al. 2006. The discussion of modern pollen and Quaternary environmental study. Progress in Natural Science, 16(6): 647–656. (in Chinese)

Xu Q H, Li Y C, Yang X L, et al. 2007. Quantitative relationship between pollen and vegetation in northern China. Science in China Series D: Earth Sciences, 50(4): 582–599.

Xu Q H, Li M Y, Zhang S R, et al. 2015. Modern pollen processes of China: Progress and problems. Science China Earth Sciences, 58(11): 1661–1682. (in Chinese)

Yang Q H, Yang Z J, Zhang Y, et al. 2019. Relationship between surface sporepollen and modern vegetation in Xarxili Nature Reserve of Xinjiang. Arid Land Geography, 42(5): 986–997. (in Chinese)

Yang Z J, Kong Z C, Yan S, et al. 2004. Pollen distribution in topsoil along the Daxigou valley in the headwaters of the Urumqi river, the Central Tianshan Mountains. Arid Land Geography, 27(4): 543–547. (in Chinese)

Yang Z J, Zhang Y, Bi Z W, et al. 2011. Surface pollen distribution in the southern slope of Tianshan Mountains, Xinjiang. Arid Land Geography, 34(6): 880–889. (in Chinese)

Yang Z J, Zhang Y, Ren H B, et al. 2016. Altitudinal changes of surface pollen and vegetation on the north slope of the Middle Tianshan Mountains, China. Journal of Arid Land, 8(5): 799–810.

Yao F L, Xia Q Q, Zhang J, et al. 2019. Pollen in surface soil at the southern slope of western Tianshan, China. Chinese Journal of Applied Ecology, 30(7): 2301–2308. (in Chinese)

Yao F L, Zhang J, Yang H J, et al. 2021a. Surface pollen distribution on the north slope of Bogda Mountain, Xinjiang, China. Ecology and Environmental Sciences, 30(3): 466–474. (in Chinese)

Yao F L, Ma C M, Zhu C, et al. 2021b. Relationship between surface pollen and vegetation on the northern slope of West Tianshan Mountains, China. Acta Palaeontologica Sinica, 60(3): 471–482. (in Chinese)

Yao Y F, Wang X, Xie G, et al. 2015. Holocene vegetation succession and climate-environment change in Xinjiang Region. Chinese Science Bulletin, 60(31): 2963–2976. (in Chinese)

Yu G, Tang L Y, Yang X D, et al. 2001. Modern pollen samples from alpine vegetation on the Tibetan Plateau. Global Ecology and Biogeography, 10(5): 503–519.

Yu P T, Liu H Y. 1997. Surface pollen and its climatical significance of vertical zone in Beitai, Xiaowutai Mountain. Acta Scientiarum Naturalium Universitatis Pekinensis, 33(4): 475–484. (in Chinese)

Zhang H, Zhang Y, Yang Z J, et al. 2013. Surface pollen research of Nanshan region, Shihezi City in Xinjiang. Acta Ecologica Sinica, 33(20): 6478–6487. (in Chinese)

Zhang N, Ge Y W, Li Y C, et al. 2021. Modern pollen-vegetation relationships in the Taihang Mountains: Towards the quantitative reconstruction of land-cover changes in the North China Plain. Ecological Indicators, 129: 107928, doi: 10.1016/j.ecolind.2021.107928.

Zhang W S, Fan B S, Li Y C, et al. 2019. Pollen record of precipitation changes during the Younger Dryas and Early Holocene in the North China Plain. Quaternary International, 532: 116–125.

Zhang W S, An C B, Zhang Y, et al. 2022. Holocene precipitation changes in the Balikun basin based on high-resolution sporopollen quantitative reconstruction. Quaternary International, 631: 69–81.

Zhang Y, Kong Z C, Yan S, et al. 2006. Fluctuation of *Picea* timber-line and paleo-environment on the northern slope of Tianshan Mountains during the late Holocene. Chinese Science Bulletin, 51: 1747–1756.

Zhang Y J, Duo L, Pang Y Z, et al. 2018. Modern pollen assemblages and their relationships to vegetation and climate in the Lhasa Valley, Tibetan Plateau, China. Quaternary International, 467: 210–221.

Zhao K L, Li X Q. 2013. Modern pollen and vegetation relationships in the Yili Basin, Xinjiang, NW China. Chinese Science Bulletin, 58: 4133–4142.

Zhao N N, Yang Z J, Ning K, et al. 2019. A comparative study on the relationship between surface pollen and vegetation on the north and south slopes of the northern Tianshan mountains. Journal of Arid Land Resources and Environment, 33(12): 117–126. (in Chinese)

Zhao N N, Yang Z J, Ning K, et al. 2020. Relationship between surface pollen and vegetation in the Qaidam Basin. Arid Zone Research, 37(4): 1068–1078. (in Chinese)

Zhao Y J, Li Y C, Zhang Z, et al. 2022. Relationship between modern pollen assemblages and vegetation in the Bashang typical steppe region of North China. Ecological Indicators, 135: 108581, doi: 10.1016/j.ecolind.2022.108581.

Zhao Y T, Miao Y F, Fang Y M, et al. 2021. Investigation of factors affecting surface pollen assemblages in the Balikun Basin, central Asia: Implications for palaeoenvironmental reconstructions. Ecological Indicators, 123: 107332, doi: 10.1016/j.ecolind.2020.107332.